

Inverse Radiative Transfer Analysis for Ocean Optics

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Award Number N000149610006

LONG-TERM GOALS

The long-term goal of this research is to support the work of ocean optics experimentalists by developing analytical and numerical methods for solving radiative transfer inverse and forward problems. The ongoing research on inverse problems includes methods for obtaining the sea water absorption and scattering coefficients, the bottom albedo, or the spatial profile of internal sources (e.g., inelastic scattering, bioluminescence, and/or fluorescence) from light field measurements at a single wavelength. New techniques for solving forward radiative transfer problems are also investigated to help with the development of methods for solving inverse problems.

SCIENTIFIC OBJECTIVES

The short-term objectives of the work on solving single wavelength inverse problems were to develop and numerically test methods for the determination of

- the absorption and backscattering coefficients,
- the bottom albedo,
- the spatial dependence of sources (such as layers of bioluminescence), and
- the sea surface albedo

from in-water light field measurements. The short-term objective of the multiple wavelength inverse problem research was to develop an approach for determining

- the water constituent concentrations

from remote sensing reflectance measurements and single scattering albedo spectra. The short-term objectives of the work on solving forward problems were

- the extension to general geometry of the analysis for the design of an integrating cavity absorption meter to measure the absorption coefficient in sea water,
- the investigation of the possibility of peaking of the scalar irradiance just beneath the sea surface, and
- the development of a scalar radiative transfer equation that approximately accounts for the effects of polarization, which otherwise must be analyzed with a vector radiative transfer equation.

APPROACH

The radiative transfer equation is the basis for most of the analytical development and numerical testing of single wavelength inverse methods. These methods, because they are derived directly from the

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 1998		2. REPORT TYPE		3. DATES COVERED 00-00-1998 to 00-00-1998	
4. TITLE AND SUBTITLE Inverse Radiative Transfer Analysis for Ocean Optics				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Washington, Department of Mechanical Engineering, Box 352600, Seattle, WA, 98195				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002252.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

radiative transfer equation, require little or no iteration and therefore are especially useful for processing large amounts of data. The methods are an alternative to the iterative methods of solving inverse problems, such as those developed by Gordon and co-workers (Refs. 1&2). For the multiple wavelength inverse method a neural network approach was implemented. The methods for forward problems also are based on the radiative transfer equation except for the analysis of a convex shaped integrating cavity which involved a chord method that generalizes the spherical cavity approach of Kirk (Ref. 3).

The research was conducted with the assistance of University of Washington graduate students Dane Hobbs, Robert Leathers and Lydia Sundman, and Prof. Collin Roesler of the University of Connecticut.

WORK COMPLETED

Inverse Problem Analyses

- *Inherent Optical Property Determination.* An algorithm for estimating the absorption coefficient a and the backscattering coefficient b_b from measurements of the upward and downward irradiances $E_u(z)$ and $E_d(z)$ has been published (Ref. 4). With this method the reflectance ratio $R(z)$ and the downward diffuse attenuation coefficient $K_d(z)$ were obtained from $E_u(z)$ and $E_d(z)$, and the values of the inherent optical properties R_∞ and K_∞ were estimated from $R(z)$ and $K_d(z)$, respectively. For an assumed scattering phase function β/b there are unique correlations between the values of R_∞ and K_∞ and those of a and b_b that can be derived from the radiative transfer equation.

Equations for the preceding approach were extended to the use of the normally-directed upward radiance $L_u(z)$ and the downward irradiance $E_d(z)$, as reported in Refs. 5 and 6. The equations were tested with numerically simulated data as well as with measurements taken in Long Island Sound. A Satlantic Upwelling Radiance Sensor OCR-200 was used to obtain $L_u(z)$ and a Satlantic Downwelling Irradiance Sensor OCI-200 was flipped vertically between casts to obtain alternatively $E_u(z)$ and $E_d(z)$. Profiles of $a(z)$ obtained from the Satlantic measurements with the use of the algorithms were compared with those obtained with a WetLabs ac-9 instrument.

- *Bottom Albedo Determination.* Two reflectance models were developed to estimate the albedo of the sea bottom in optically shallow waters. Either measurements of the downward and upward irradiances or the normally directed upward radiance and the downward irradiance are required. Numerical testing with solutions of the forward problem were used to test the efficacy of the algorithms and to compare their performance to other algorithms in the literature. This work is reported in Refs. 5 and 7.

- *Spatially Distributed Source.* A method was numerically tested and published in Ref. 8 for determining the spatial distribution of a source (e.g., due to inelastic scattering, fluorescence, or bioluminescence) from upward and downward irradiance measurements at a single wavelength in seawater of known absorption and scattering properties. The algorithm uses measurements at two depths located an arbitrary distance apart and solves for two parameters that fit an exponential or linear source shape. Estimates from neighboring measurement pairs can be pieced together to produce a solution for complex spatially-dependent source shapes.

In Ref. 9 the preceding approach was generalized to enable the determination of the spatial profile of a source from radiance measurements. The algorithm can be used with an above-water radiometer or, more accurately, with in-water measurements.

- *Sea Surface Albedo Determination.* Closed-form analytical equations have been developed to determine the single scattering albedo $\omega = b/(a+b)$ of near-surface waters using the ratio of the in-water upward-to-downward irradiance ratio. The algorithm is implemented with an iterative computation of the asymptotic diffuse attenuation coefficient (K) and the Chandrasekhar H -function, both of which can be conveniently expressed in closed form for isotropic scattering. The effects of anisotropic scattering are corrected using the Gordon parameter $G = b_b/(a+b_b)$. The work is presented in Ref. 10.

- *Water Constituent Concentrations Determination.* Multilayer perceptron neural networks were trained with back-propagation algorithms to obtain the concentrations of water constituents from multi-spectral estimates of the single scattering albedo ω . The value of ω can be obtained either from in-water measurements (e.g., Ref. 10) or from the remote sensing reflectance R_{RS} . See Ref. 11.

Forward Problem Analyses

- *Integrating Cavity Absorption Meter Design.* We have generalized the analysis for the design of integrating cavity absorption meters to account for the probability of photon survival in general geometries. Numerical calculations reported in Ref. 12 have been performed that illustrate the effect of non-spherical geometries on the estimated absorption coefficient.

- *Scalar Irradiance Peaking Analysis.* Under certain conditions the scalar irradiance $E_0(z)$ can increase with penetration depth near the surface, even if there are no internal sources at the wavelength of interest. The analysis and numerical examples published in Ref. 13 help quantify the magnitude and location of potential $E_0(z)$ peaks in source-free ocean waters or sea ice and the dependence of the phenomenon on the seawater optical properties and surface illumination.

- *Approximate Scalar Radiative Transfer Equation For Polarization Analysis.* An asymptotic analysis of the radiative transfer equation with polarization was developed in Ref. 14 that leads to a renormalized scalar equation for the total specific intensity of radiation that is one of the four Stokes parameters. The resulting scalar equation can be used without the complexity of performing vector radiative computations since it merely requires an adjustment of the Legendre coefficients of the scattering phase function using elements of the 4×4 scattering phase matrix.

RESULTS

Inverse Problem Analyses

- *Inherent Optical Property Determination.* Good estimates of a and the Gordon parameter $G = b_b/(a+b_b)$ were obtained from R_∞ and K_∞ if the true scattering phase function was not greatly different from the assumed function. The method works best in deep homogeneous waters, but computationally has been shown to be applicable in some cases to stratified waters. It is important to use a realistic scattering phase model (e.g., a Petzold phase function) in the inverse solution because b_b is sensitive to the backscattering portion of the phase function.

- *Bottom Albedo Determination.* The new method developed here requires measurements from only one site whereas a previously developed method requires additional measurements at a nearby deep-water site in order to provide a reference base for the measurements at the desired site. Both the new and old methods can utilize measurements away from the sea bottom to avoid self-shielding errors.

- *Spatially Distributed Source Determination.* Numerical tests have illustrated the sensitivity of the algorithm to depth, measurement spacing, chlorophyll concentration, sensor noise, and uncertainty in the *a priori* assumed inherent optical properties. The algorithm for downward and upward irradiance measurements works well with moderate sensor noise and moderate uncertainties in the inherent optical properties, regardless of whether the assumed and true profiles are the same shape. It is believed that the most practical application of the algorithm requiring irradiance measurements would be for profiling large layers whereas that requiring radiance measurements would be for locating regions of interest within a large layer for more extensive profiling efforts.

- *Sea Surface Albedo Determination.* The algorithm requires that the fractions of direct, monodirectional illumination and diffuse (cardioidal) illumination be known, as well as an approximate value for b_b . Numerical tests using simulated values of the irradiance ratio for realistic Case 1 waters showed that the algorithm can be used in some circumstances to obtain a good estimate of ω .

- *Water Constituent Concentrations.* Networks using R_{RS} measurements at only seven wavelengths returned excellent estimates, in the absence of measurement noise, of the concentrations of the five constituents used in the tests. Larger networks using more wavelengths were required to give good estimates from noisy inputs.

Forward Problem Analyses

- *Integrating Cavity Absorption Meter Design.* The performance of a cylindrically shaped cavity is easily analyzed with the new equation for the survival probability of photons uniformly and isotropically illuminating the cavity. The error in the use of the homogeneous energy density assumption can now be assessed for existing meters rather than for one of an assumed spherical shape.

- *Scalar Irradiance Peaking Analysis.* Peaking is most pronounced when the incident illumination is strongly directed at the zenith angle, and the location of maximum is deepest when the asymmetry of the scattering phase function is large. The presence of internal reflection due to the index of refraction mismatch at the air-sea interface greatly reduces the chance of $E_0(z)$ peaks being present, making a maximum in $E_0(z)$ below the surface only possible if $\omega > 0.95$ in homogeneous waters or potentially smaller values if ω increases with depth.

- *Approximate Scalar Radiative Transfer Equation For Polarization Analysis.* Numerical results demonstrated the improved accuracy of the renormalized scalar equation for the intensity over the usual unpolarized approximation. The percent error obtained for the asymptotic diffuse attenuation coefficient using the approximate scalar equation that incorporates effects of polarization is generally of the order of a factor of five smaller than the error if polarization effects are totally ignored. The results vary considerably with the albedo of single scattering and the scattering phase function.

IMPACT/APPLICATION

Determination of inherent optical properties is a primary goal of optical oceanographers for use in environmental monitoring. Inversion of the light field to determine inherent optical properties from apparent optical properties has direct application to in-water and remote sensing of ocean color. Since the chlorophyll concentration cannot be used to correlate the optical properties for coastal waters, the inversion is more difficult for such waters than for open ocean waters. The analytically-based algorithms developed here will help in this inversion process and in obtaining optical closure.

The analysis for an integrating cavity absorption meter of general geometry will be important for the future design of meters used to measure waters with large absorption coefficients.

TRANSITIONS

The efficacy of our approach for the determination of a and b_b from either $E_u(z)$ and $E_d(z)$ or the vertically upward radiance $L_u(z)$ and $E_d(z)$ was tested by Robert Leathers and Collin Roesler with experimental data collected from stations in Long Island Sound.

RELATED PROJECTS

I was a lecturer in the Ocean Optics Summer Course at Friday Harbor Laboratories that was directed by Mary Jane Perry of the University of Washington and funded by ONR.

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